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**A NEAR-REAL-TIME FULL-PARALLAX  
HOLOGRAPHIC DISPLAY FOR REMOTE OPERATIONS**

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**ABSTRACT**

A near-real-time, full-parallax holographic display system was developed that has the potential to provide a 3-D display for remote handling operations in hazardous environments. The major components of the system are: (1) a stack of three spatial light modulators (3-SLM stack) which serves as the object source of the hologram; (2) a near-real-time holographic recording material (such as thermoplastic or photopolymer); and (3) an optical system for relaying SLM images to the holographic recording material and to the observer for viewing.

**I. INTRODUCTION**

Over the past 30 years, holography has made substantial contributions to several fields. Holography is a core technology in nondestructive testing to find hidden defects beneath surfaces, in interferometry to measure small mechanical displacements, and in optical pattern recognition. Three-dimensional (3-D) holographic displays are common in art and advertising and embossed holograms provide enhanced security for credit cards, entertainment tickets, record albums, and clothing labels. Holographic displays, however, are typically time-consuming to initially generate and are usually static. This paper describes the prototype development of the Holographic Enhanced Remote Sensing System (HERSS) for generation of near-real-time 3-D snapshots of remote equipment and objects<sup>1</sup>. This effort was conducted over the period 1988 through 1990.

**II. HERSS GOALS**

The key goal of the HERSS program was to generate a near-real-time, full-parallax (i.e., having both horizontal and vertical parallax) holographic snapshot of remote objects using data collected by a conventional imaging system. Specifically, the image data would contain the surface points of the remote objects and could be collected, for example, using a laser range scanner. The goal of the prototype system was to generate a 3-D snapshot of the remote image data in 30 seconds or less. While 30 seconds may seem a relatively long interval, this image update period was still deemed adequate for the intended application and is considered to be near real time in the context of remote operations. Furthermore, generating a *full-parallax* holographic image in this time frame is an ambitious goal which challenges the performance capabilities of currently available components in critical parts of the system.

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Certain subgoals were also established for HERSS development including:

- Map the surface points occupying a 152 x 152 x 152 mm (6 x 6 x 6 in) cube at the remote work site onto a holographic volume of the same size;
- Provide a depth resolution in the 3-D display of 2 to 3 mm (0.08 to 0.1 in), and;
- Provide a capability to overlay graphics onto the hologram.

### III. APPROACH

The HERSS concept for generating a holographic snapshot involves four basic steps. First, the numerical representation of object surface points is collected. Second, the numerical data base is "sliced" into 2-D depth planes with a finite thickness. If the slice thickness is 3 mm, then each 2-D depth plane contains the surface points of the objects in a unique 152 x 152 x 3 mm (6 x 6 x 0.1 in) region. That is, all surface points in a 3 mm region of depth are compressed into one 2-D plane. Third, each 2-D plane is sequentially transmitted to a computer-addressable spatial light modulator (SLM). The SLM acts as the "coherent" object source for the hologram. Each SLM image is exposed on a near-real-time holographic recording material (HRM), such as thermoplastic<sup>2</sup> or photopolymer<sup>3</sup>, using a plane-by-plane multiple exposure process. Images are sequentially transmitted to the SLM for exposure until all depth planes are recorded. Finally, the HRM is developed through a heating process for the thermoplastic medium or through a UV bath for the photopolymer.

When the HERSS project was initiated, the viability of using an SLM as a holographic object source had been demonstrated with the production of holographic stereograms on photographic film<sup>4</sup>. Furthermore, the viability of multiple-exposure holography had also been demonstrated with the generation of a 3-D view of CAT scan data by multiply exposing superimposed CAT cross-sections onto standard silver halide film<sup>5</sup>. No published reports, however, were available that documented using an SLM as a holographic object source for a near-real-time HRM. Furthermore, no reports documented multiple exposure of thermoplastic or photopolymer. It was unknown how many exposures each of these HRMs could store before image quality would be seriously degraded.

### IV. BASELINE CONFIGURATION

#### A. Optical Configuration

The baseline optical system, as shown in Figure 1, was designed to generate an image-plane transmission hologram. For baseline testing, an nView SLM was selected as the holographic object source and a thermoplastic camera developed by Newport Corporation (based on an original design by Honeywell) was selected as the near-real-time HRM. The nView SLM had an addressable 152 x 152 mm (6 x 6 in) area. Because the Newport thermoplastic material was only available in a 38 mm format, this created the need for magnifying optics to enlarge the holographic image for the observer. Thus, the optical configuration served three functions: (1) direct an expanded object beam to the SLM and an expanded reference beam to the HRM; (2) relay the SLM object beam image to the HRM; and (3) magnify the HRM image for viewing.

#### B. Plane-by-Plane Exposure

The plane-by-plane multiple exposure technique initially employed by HERSS is illustrated in Figure 2. Laser light transmitted through open SLM-cells outlines the shape of the remote object(s) for a particular depth slice. A projection lens is used to relay the SLM image to the HRM for exposure. The SLM is in a fixed position while the projection lens is mounted on a sliding table that has a 152 mm (6 in) travel. When the first depth plane is exposed, the table is positioned at one end of its travel. After each exposure, the table is moved to the next depth plane location. Unique depth plane images are sequentially transmitted to the SLM for exposure on the thermoplastic. This move-display-expose cycle is repeated until the entire object volume is recorded. When the exposure process is complete, the material is developed and a single holographic frame is viewable.

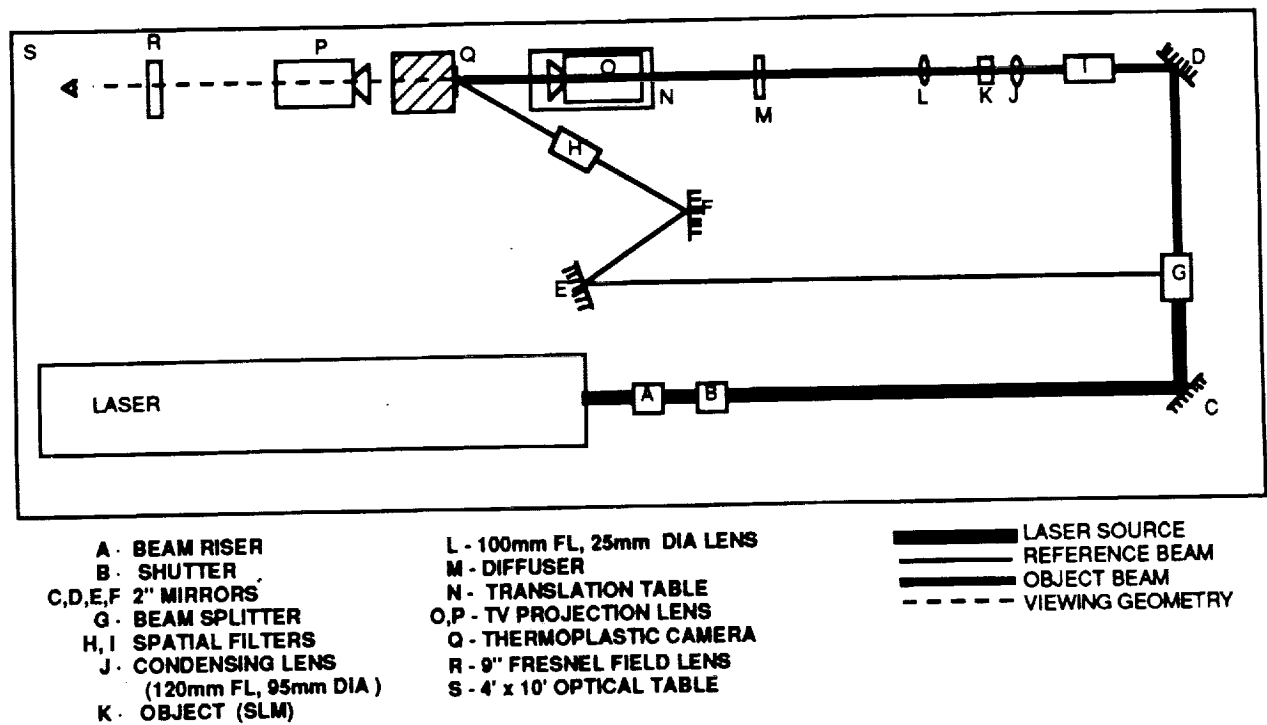


Fig. 1. Baseline Optical Configuration. The schematic portrays the optical paths of the object and reference beams as well as the viewing geometry of the system. The object beam passes through the SLM (K) on its path to the recording material (Q). The reference beam is directed to (Q) where it interferes with the object beam. This interference pattern stores the intensity and phase information necessary to reconstruct the 3-D image for the viewer.

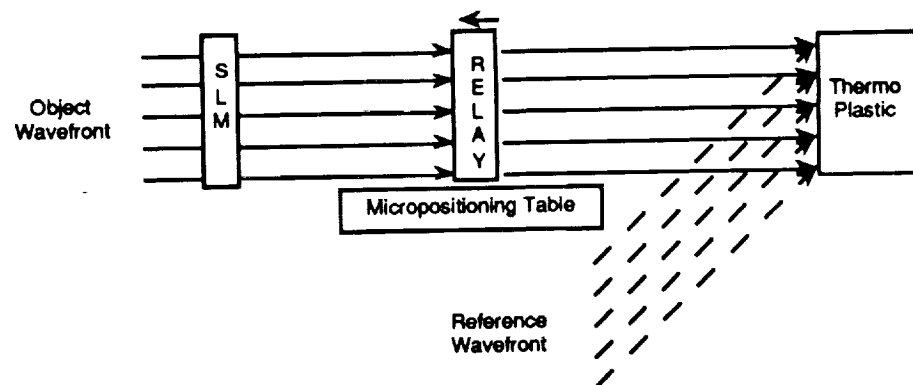


Fig. 2. Baseline Plane-by-Plane Exposure Method

## C. Results

Early experimentation with the baseline configuration yielded two major successes regarding holographic image generation and quality including:

- Generation of a hologram was possible while the relay lens was mounted on a motor-driven micropositioning table. Initially there was some concern that vibration transmitted from the stepper motor to the table would negatively affect the SLM light pattern, resulting in a failed hologram.
- Twenty depth planes (using a patterned glass target, not an SLM image as the object source) could be superimposed through multiple exposure onto the thermoplastic without serious degradation of image quality. (The recordings were made using a K3 ratio of 1 and an exposure energy of  $7 \mu\text{J}/\text{cm}^2$  with  $1/n^{\text{th}}$  the exposure energy for any single depth plane.)

However, drawbacks regarding image quality were also noted including:

- A sharp holographic image could not be generated using the nView SLM as the holographic object source. This was attributed to a low contrast level of the SLM. Considerable light leakage through closed cell areas was evident.
- The holographic image was distorted by the optical components that relayed the SLM image onto the HRM as well as by optical components that magnified the image for viewing.

Regarding HERSS goals, the following conclusions were drawn:

- To meet the display-depth-resolution goal of 2 to 3 mm (0.08 to 1.0 in), at least 51 depth planes would need to be recorded in the 152 mm (6 in) holographic depth. With 20 superimposed depth-planes, a depth resolution of only 7.5 mm (0.3 in) could be achieved.
- Even though a 152 mm (6 in) holographic image depth could easily be achieved, the optically-relayed image was laterally limited to 114 mm (4.5 in). This was the direct result of a relatively small Newport thermoplastic film format. Optics to minify and relay the SLM-image (152 x 152 mm) to the thermoplastic (38 x 38 mm) as well as optics to magnify and relay the thermoplastic image to the observer could only practically meet a threefold minification or magnification. A fourfold factor would require very low-f/# optics that are both difficult to produce and are prohibitively expensive. A larger aperture film-based thermoplastic system was evaluated; unfortunately, the efficiency and reliability of the system were inadequate.
- To record 51 image planes using the plane-by-plane exposure technique would require about 64 seconds for exposure and 30 seconds for development. Each exposure consists of moving the micropositioning table to the next depth position (250 msec) and allowing time for table vibrations induced by the motor to dissipate (1000 msec). While the 30-second development time could be reduced to less than 100 msec via modification of the electronic components heating the thermoplastic<sup>2</sup>, the plane-by-plane exposure method itself is still a time-consuming process.

## **V. REVISED CONFIGURATION**

A phase conjugate optical configuration was devised to circumvent the image distortion produced by the baseline optical system. A multiplane exposure technique was also devised to (1) increase the number of image planes recorded in a holographic snapshot and (2) reduce exposure time. For the revised configuration testing, the nView SLM was replaced by three Sharp SLMs which were extracted from a SharpVision Projection System. The Sharp SLMs are monochromatic TFT-based units that are 2.4 inches wide by 1.8 inches high, having a resolution of 384 x 240 pixels and a 30:1 contrast ratio. Testing was continued using Newport thermoplastic as the HRM. Some testing was also conducted using Du Pont HRF-700 photopolymer as the HRM.

### A. Phase Conjugate Optical Configuration

The revised optical configuration, as shown in Figure 3, was based on the principles of phase conjugation and reverse ray tracing<sup>6,7</sup>. In a phase conjugate optical system, the optics used to generate the hologram are the same

optics used to view the hologram. Specifically, during hologram generation, the object and reference beam wavefronts interfere at the front face of the holographic recording material, as is required for generation of a transmission hologram. During viewing, the reference wavefront is transmitted through the rear of the recording material and travels in a reverse path through the optical system to reconstruct the original object wavefront. Image distortions are still induced by the optics during hologram generation. However, these distortions are removed during the phase conjugate reconstruction when the light diffracted by the hologram is transmitted through the optical system in a reverse path to produce the 3-D image that the observer views.

The phase conjugate configuration also provides a one-to-one correspondence between the size of the SLM image and the size of the recorded holographic image. This means that the lateral dimensions of the holographic image are equal to the lateral dimensions of the SLM. Thus, magnifying optics to enlarge the image for viewing can be eliminated.

### B. Multiplane Exposure

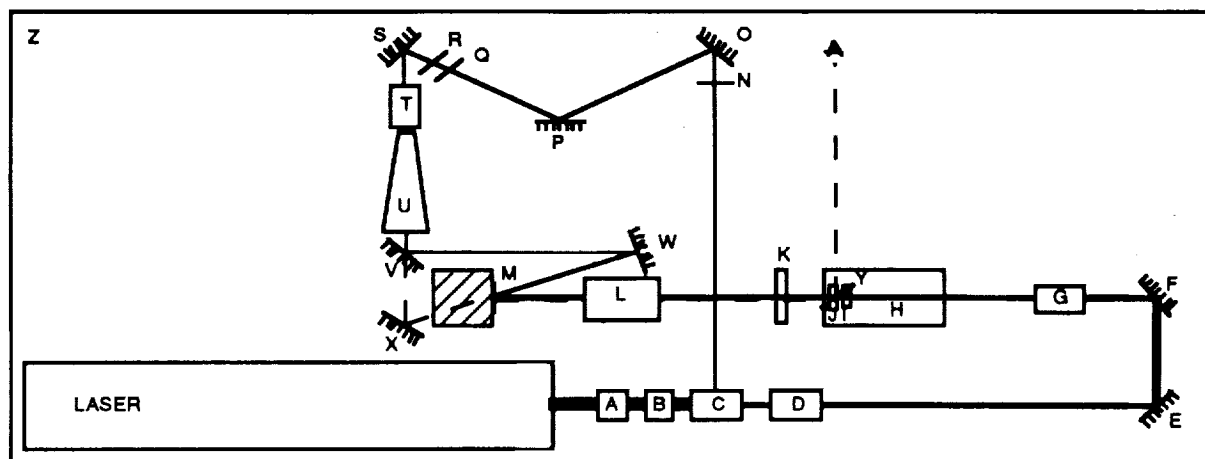
To circumvent the multiple exposure limitation of the thermoplastic, a multiplane exposure method was devised as illustrated in Figure 4. Basically, the method uses a stack of three SLMs. Each SLM in the stack is slightly separated in the axial plane to represent the real distance between image slices. During the multiplane exposure process, three depth plane images are simultaneously exposed on the thermoplastic instead of only one depth plane at a time. The revised technique has the potential to increase the number of image planes recorded in a holographic frame because, with only 17 exposures, 51 image planes could be recorded.

In addition to increasing the information content within a holographic frame, another key benefit of this technique is the potential to reduce the time to generate a single holographic frame. If 51 images are recorded in 17 exposures instead of 51 exposures, then 34 micropositioning table moves can be eliminated as well as the concomitant settle time for each table move. This provides a significant savings of time considering table move and settle times of 250 msec and 1000 msec, respectively.

### C. Results

Key successes of the phase conjugate configuration and the multiplane exposure technique included:

- Distortion-free holographic imaging with the phase conjugate reconstruction.
- Image quality comparable to, if not better than, the baseline.
- A 95% increase in the number of image planes that could be recorded on the thermoplastic HRM. Specifically, 39 depth planes could be superimposed with 13 exposures of the 3-SLM stack before image quality was seriously degraded. With the baseline plane-by-plane exposure technique, only 20 depth planes could be superimposed before quality degraded. This successful recording of 39 depth planes demonstrates the viability of the stacking method. (The recordings were made using a K ratio of 1 and an exposure energy of  $7 \mu\text{J}/\text{cm}^2$  with  $1/n^{\text{th}}$  the exposure energy for  $n$  exposures of the stack.)
- The resolution and contrast of the Sharp SLMs provided acceptable imaging.
- Experimentation with alternative SLM-addressing schemes revealed a flexibility in selecting how surface shapes would be represented. Both a "bright on dark" and a "dark on bright" holographic image were generated. A "bright on dark" image was created if *open* SLM pixels represented surface points. If *closed* SLM pixels represented surface points, the light transmitted through the SLM to the HRM resulted in a "dark on bright" image. The latter option is relatively simple to implement — pixels containing shape information are closed while all other pixels are open. The former option requires that pixels containing shape information are open while others are closed. However, SLM pixels in the stack that are in front of or behind open image-containing pixels must also be opened to allow light to be transmitted. Even though more difficult to implement, the "bright on dark" technique was adopted for prototype testing because the non-image light in the "dark on bright" technique could possibly degrade the multiple exposure recording capability of the film.



- |                          |   |                  |
|--------------------------|---|------------------|
| A - BEAM RISER           | O,P,S - 2" MIRROR                               | LASER SOURCE     |
| B - SHUTTER              | Q - POLARIZER                                   | REFERENCE BEAM   |
| C - BEAM SPLITTER        | R - ATTENUATOR                                  | OBJECT BEAM      |
| D - ROTATIONAL POLARIZER | T - SPATIAL FILTER                              | VIEWING GEOMETRY |
| E,F - 2" MIRROR          | U - COLLIMATOR                                  |                  |
| G - SPATIAL FILTER       | V - 4" MIRROR ON KINEMATIC BASE (Generate Mode) |                  |
| H - TRANSLATION TABLE    | W - 4" MIRROR                                   |                  |
| I - DIFFUSER             | X - 4" MIRROR (Viewing Mode)                    |                  |
| (Generate Mode)          | Y - 8" x 11" MIRROR (Viewing Mode)              |                  |
| J - 3-SLM STACK          | Z - 4' x 10' OPTICAL TABLE                      |                  |
| (Generate Mode)          |   |                  |
| K - 9" FL FRESNEL LENS   |   |                  |
| L - TV PROJECTION LENS   |   |                  |
| M - THERMOPLASTIC CAMERA |   |                  |
| N - HALF-WAVE PLATE      |   |                  |

Fig. 3. Phase Conjugate Optical Configuration. The schematic portrays the optical paths of the object and reference beams and the viewing geometry of the system. The object beam passes through the 3-SLM stack (J) on its path to the recording material (M). The reference beam is also directed to (M) where it interferes with the object beam during hologram recording. During reconstruction, the object beam is blocked by removing the mirror on the kinematic mount (V). This allows the reference beam to reflect from mirror (X) onto the rear of the holographic recording plate. The diffracted light then passes back through the optics in the direction of the observer. During viewing mode, the 3-SLM stack (J) and diffuser (I) are removed and a mirror (Y), oriented at a 45° angle from the optical path, is mounted on the micropositioning table (H) in place of the SLM stack.

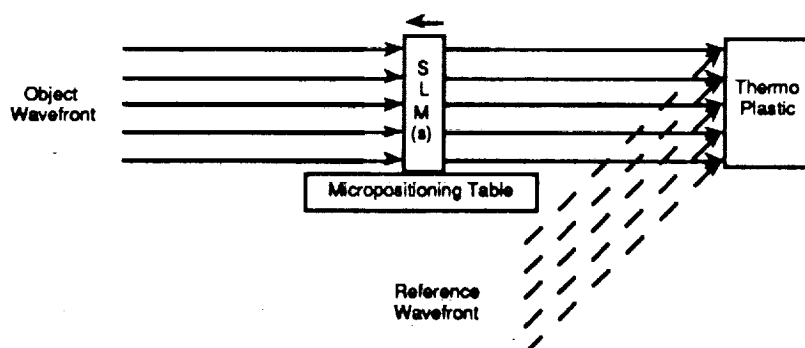


Fig. 4. Multiplane Exposure Method

Drawbacks regarding image quality were also noted:

- Concerning the thermoplastic material, there was a brightness variation in the holographic image. Brightness varied as a function of viewing angle and was particularly pronounced in the horizontal plane. This image brightness variation with viewing angle was attributed to the diffraction efficiency rolloff of the thermoplastic film with holographic fringe spatial frequency variation above and below the optimum value. Object rays that are recorded at the optimum spatial frequency of 800 line pairs per millimeter (lpm) will exhibit the optimum diffraction efficiency and will be bright and have high contrast. In our configuration, this optimum spatial frequency occurred for normally incident object rays. Rays that are either to the left or right of the normal will be recorded with higher or lower spatial frequency, a corresponding lower diffraction efficiency, and a corresponding shift in brightness.
- A maximum viewing field angle of only 15-20 degrees could be achieved with the thermoplastic camera. This was also attributed to the limited recording resolution of the thermoplastic.
- Concerning multiplane exposure, depth positions were clearly discernable from one 3-SLM stack position to the next. However, it was not possible to discern the difference in depth within a stack. It is likely that this effect is attributable to the relatively small field-of-view of a single pixel using the "bright on dark" SLM-addressing technique (i.e., only one pixel in front of and behind an image-containing pixel is opened).
- Concerning use of the 3-SLM stack for multiplane exposure, a faint Moire pattern could be seen in the background of the holograms when the observer's head moved through the field of view. This problem is attributed to a slight misalignment in the SLM stack. Each SLM has a periodic pattern of thin opaque (5-10 micron) electronic structures that separate the pixels. Superposition of the nonaligned electronic structures causes the Moire pattern resulting in some obscuration of the desired intensity pattern.

Regarding HERSS goals, the following conclusions were drawn:

- With 39 superimposed depth-planes, a depth resolution of only 3.9 mm (0.15 in) could be achieved. This is still short of the desired display-depth-resolution goal of 2 to 3 mm (0.08 to 1.0 in) or at least 51 depth planes in the 152 mm (6 in) holographic depth.
- The lateral dimensions of the holographic image was limited to the lateral dimensions of the Sharp SLM or 61 x 46 mm (2.4 x 1.8 in). While the baseline nView SLM could meet the size criteria, image quality was very poor. The Sharp SLM size limitation is expected to be alleviated when larger format SLMs, currently under development, are released. The development of a Sharp SLM with a 5.5 inch diagonal and a 100:1 contrast ratio is underway<sup>8</sup>.
- To expose 51 image planes using the multiplane exposure technique would require about 21 seconds using the thermoplastic material.

#### D. Testing and Results using Photopolymer as the HRM

Because of the relatively low recording resolution and small format of the thermoplastic, hologram generation using a newly released Du Pont photopolymer (HRF-700 Series) was undertaken. The photopolymer is a volume recording material with a resolution of over 4000 lpm. This means that the photopolymer can store much more information than thermoplastic which has only 800 lpm. An improved viewing field angle is also possible with the higher recording resolution. Furthermore, the photopolymer is available in sheet sizes 8.5 by 11 inches allowing an ideal HRM size of 51 x 51 mm (2 x 2 in). As previously mentioned, affordable optics to minify the SLM image onto the HRM can only practically achieve a threefold minification from 152 x 152 mm (6 x 6 in) to 51 x 51 mm (2 x 2 in). It is also noteworthy that the minification of the SLM image onto a smaller format HRM is critical for minimizing exposure time. Given a fixed laser power, the light intensity per unit area on the HRM increases as the size of the HRM decreases. Thus, as HRM size decreases, exposure time is also decreased.

Due to time constraints, experimentation with the photopolymer was limited to testing with the baseline plane-by-plane exposure technique. Testing focused on determining the maximum number of image planes that could be recorded. The most dramatic testing result was that a high quality image could be produced which stored 40 image planes. This was a 100% increase over the capability of the thermoplastic using the plane-by-plane exposure technique. Furthermore, given additional research, the experimental team was confident that an even greater number

of depth planes could be stored on the photopolymer. However, as the number of exposures increase and the energy per exposure decreases (i.e., with each plane assigned  $1/n^{\text{th}}$  of the total exposure requirement), it may be necessary to first energize the material to activate the polymerization process.

A drawback of the photopolymer, however, is a slower photospeed compared to the thermoplastic. Exposure time for this material is approximately 24 - 30 seconds using an argon-ion laser (with one watt energy on a single line); development time is instantaneous with the UV bath. To record 51 image planes on photopolymer using the plane-by-plane technique would require about 88 to 94 seconds. Considering a system employing the 3-SLM exposure method, a holographic frame with 51 image planes can theoretically be recorded in approximately 45 seconds (21 seconds for the 17 move-settle cycles plus 24 seconds for exposure).

## VI. CONCLUSIONS

A full-parallax holographic display system was developed that can generate 3-D snapshots of a remote work site using data gathered by a conventional imaging system (e.g., a laser range finder). The major components used to generate a holographic snapshot are: (1) a stack of three spatial light modulators (3-SLM stack) which serves as the object source of the hologram; (2) a near-real time holographic recording material (e.g., thermoplastic or photopolymer); and (3) an optical system for relaying SLM images to the holographic recording material and to the observer for viewing.

The viability of the HERSS system concept was demonstrated during prototype development and testing. However, as with any technology development effort, there is a complex set of design tradeoffs that affect program goals. For HERSS, a major tradeoff exists between information content of the display and display update rate. Simply stated, as the number of recorded depth planes increases, recording time increases. Another major tradeoff exists between image quality and display update time. For example, while the recording resolution of photopolymer (at least 4000 lpm) is far superior to that of the thermoplastic material (800 lpm), the energy requirements to expose photopolymer (at least 10 mJ/cm<sup>2</sup>) is three orders of magnitude greater than thermoplastic (7  $\mu$ J/cm<sup>2</sup>) resulting in a slower update rate.

Individual component improvements can lessen the impact of these tradeoffs. For example, to achieve a high quality image with a relatively fast display update rate, a thermoplastic material with greater resolution or a photopolymer with a faster photospeed is desirable. Furthermore, to achieve the goal of a 152 x 152 x 152 (6 x 6 x 6 in) holographic image volume, a high-contrast SLM with lateral dimensions of 152 x 152 mm (6 x 6 in) is needed.

Future experimental efforts that use the current HERSS configuration and components can also be conducted to improve image quality and a faster display update rate. These efforts would include:

- Determine the maximum number of image planes that can be recorded on the photopolymer using the 3-SLM multiplane exposure technique. With the 3-SLM stack, it is possible that as many as 80 image planes can be recorded, thereby exceeding the HERSS depth resolution goals. Use of the 3-SLM stack also significantly reduces hologram generation time.
- Investigate the optimum SLM-pixel-addressing scheme for maximum perception of depth in the display (e.g., creation of the dark-on-bright multiply-exposed hologram).
- Investigate methods to reduce exposure time (e.g., determine the minimum settle-time for each move-display-expose cycle. It is very likely that the current 1-second settle time can be substantially reduced.)

Finally, it is important to conduct psychophysical experimentation to determine what configuration options will result in the most accurate perception of discrete depth planes.

Full-parallax 3-D displays have the potential to provide safer and perhaps more timely remote work operations. While the design challenges associated with developing such displays are demanding, the effort is warranted. It is only with a full-parallax display that an operator can correctly perceive the relative orientation and location of objects at any viewing angle. This is a critical requirement for control tasks in hazardous environments. Finally, the existence of such displays may also provide the opportunity to bring remote equipment operation to close-in tasks which now require direct human control.



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